ANTIKAON ANGULAR DISTRIBUTIONS IN THE REACTION $\gamma d \to K^- \Theta^+ p \to K^- K^+ np$ NEAR THE THRESHOLD AND THE PARITY OF THE Θ^+ PENTAQUARK

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Abstract

Within spectator model we study the reaction $\gamma d \to K^- \Theta^+ p \to K^- K^+ np$ in the threshold energy region. We present the predictions for the exclusive and inclusive K^--meson angular distributions in the laboratory system for this reaction calculated for two possible parity states of the Θ^+ resonance at 1.5 and 1.75 GeV beam energies with and without imposing the relevant kinematical cuts on those parts of the sampled phase space where contribution from the main background sources, associated with the $\phi(1020)$, $\Lambda(1520)$ production as well as with the K^-p-rescattering in the final state, is expected to be dominant. We show that under chosen kinematics these distributions are sensitive to the Θ^+ parity and, therefore, can be used as a filter for the determination of its parity.

1 Introduction

The study of an exotic pentaquark baryons has received considerable interest in recent years (see, for example, refs. [1–7], which contain a review of the experimental and theoretical works on the issue) and is one of the most exciting topics of the nuclear and hadronic physics nowadays. This interest was triggered by the discovery of the narrow baryon resonance $\Theta^+(1540)$ with positive strangeness $S = +1$ by the LEPS Collaboration at SPring-8/Osaka [8] and the subsequent other experiments [9–17]. The observed state $\Theta^+(1540)$ decays into a kaon and a nucleon and has been interpreted as $q^4\bar{q}$ pentaquark with quark structure $uudd\bar{s}$. Evidence for the existence of another exotic pentaquark state $\Xi^{--}(1862)$ with mass 1.86 GeV, width about 18 MeV due to detector resolution, strangeness $S = -2$ and quark content $ddss\bar{u}$ has been reported by the NA49 Collaboration at SPS [18]. In addition, the signal of a heavy pentaquark $\Theta_c(3099)$ in which the antistrange quark in the Θ^+ is replaced by an anticharm quark was found in recent experiment [19]. Meanwhile, there have been also several experiments [20–27] at high energy in which no signals for those pentaquark baryons have been observed. Moreover, no definite structure in the K^+n invariant mass spectrum from the reaction $\gamma p \to \bar{K}^0 K^+ n$ was observed at 1540 MeV in the recent high–statistics and high–resolution experiment [28] indertaken by the CLAS Collaboration at JLab. Therefore, the existence of these baryons is still not completely established and more high–statistics experiments with different beams, targets, energies are needed to obtain a definite result for or against their existence.

The mass of about 1.54 GeV and decay width of less than 20–25 MeV of the Θ^+, extracted from the experiments [8–17], are compatible with theoretical predictions of the chiral soliton model [29]. The observed Θ^+ width reflects the experimental resolutions and its actual magnitude, as is expected [30–35] from the analysis of the kaon–nucleon, kaon–deuteron and kaon–nucleus scattering data, is limited by a few MeV level. While the isospin of the Θ^+ resonance is probably zero (see, e.g., SAPHIR [11] and CLAS [12] results concerning non–existence of the $\Theta(1540)$ in K^+p channel), the other quantum numbers of this state including spin and parity have not yet been determined experimentally. Theoretically, most models predict that Θ^+ has spin 1/2 because of its low mass, whereas their predictions on the Θ^+ parity are still controversial. Thus, for example, the positive parity of the Θ^+ is supported by the chiral soliton model [29, 36, 37], various correlated quark models [38–42], Skyrme model [43], and a lattice calculation [44]. On the other hand, such theoretical approaches as the uncorrelated quark model [45], the collective stringlike model of pentaquarks [46], the QCD sum rules [47–49], the lattice QCD [50, 51] favor a negative parity for the $\Theta^+(1540)$. So, it is unclear currently what sign of the Θ^+ parity is the correct one. The knowledge of this sign is important for distinguishing between different models mentioned above and, hence, for gaining more insight into the dynamics of low–energy QCD [52].

To help determine the parity of the Θ^+, a number of studies have been carried out to understand how the unpolarized [53–66] and polarized [59, 62–77] observables of the Θ^+ production processes, induced by the medium energy photons, nucleons, pions, and kaons on nucleon targets, depend on the parity of $\Theta^+(1540)$. Very recently, the authors of [78] have explored how the spin observables in the reaction $\pi^\pm \vec{D} \to \vec{\Sigma}^\pm \Theta^+$ near the threshold can be used to distinguish the parity of Θ^+. Obviously, the use

of the unpolarized observables for the determination of the Θ^+ parity, which do not depend very much on the theoretical ambiguities (if such observables exist), has an advantage compared to the utilizing of the spin ones, since in the first case a much simpler experimental setups and beam conditions are required for the measurements. Recently, in refs. [58, 59], the authors discussed a rather model–independent way to discriminate the Θ^+ parity from the $\gamma N \to \bar{K}\Theta^+$ reaction by looking at antikaon angular distribution. In particular, they have demonstrated that the (unpolarized) differential cross section for the reaction $\gamma n \to K^-\Theta^+$ close to the production threshold shows a clear distinction between the two opposite parities of the Θ^+ baryon. Namely, near the threshold [1] , this cross section is isotropic in the γn c.m.s. frame if the parity of the Θ^+ is positive, and it follows $\sin^2\theta'_{K^-}$ behavior (where θ'_{K^-} is the K^--meson polar production angle in the c.m.s.) when the parity of Θ^+ is negative. Therefore, measurement of the reaction $\gamma n \to K^-\Theta^+$ in the threshold energy region would allow one to determine the parity of the Θ^+ resonance [58, 59]. However, such measurement can be performed only on the bound in the nucleus neutron because of the absence of a free neutron target. Often, the bound neutron in the deuteron is used as a substitute of the free one. Thus, for instance, at JLab, the Θ^+ baryon was observed with the CLAS detector [10] as a narrow peak in the K^+n system produced in the reaction $\gamma n \to K^-\Theta^+ \to K^-K^+n$, where the target neutron was bound in the deuteron. Unfortunately, the neutron in the deuteron is not at rest and is moving with a Fermi momentum which has a component along the incident photon direction of say about $\pm$ 50 MeV/c. Though this is only a few MeV in energy, it has a huge influence on the kinematics, especially, if we are investigating the threshold phenomena. This raises the question of whether a predicted [58, 59] specific shape of the angular distribution of the $\gamma n \to K^-\Theta^+$ reaction near threshold, depending on the Θ^+ parity, survives when this reaction takes place on the moving neutron in the deuteron. It is highly desirable and useful to give a reasonable answer to this question–the main goal of the present investigation–to clarify the feasibility of experimental determination of the parity of an exotic pentaquark baryon state Θ^+ by measuring this distribution. In doing so, it is needed also to take into consideration the fact that the two–body reaction $\gamma n \to K^-\Theta^+$ is directly unobserved, since Θ^+ can be detected only from its hadronic decays $\Theta^+ \to K^+n$ [8, 10–12] and $\Theta^+ \to K^0p$ [9, 13–17].

In this paper we perform a detailed analysis of the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$ in the threshold energy region. We present the predictions for the exclusive and inclusive antikaon angular distributions in the laboratory system for this reaction obtained in the framework of a simple spectator model for two possible parity states of the Θ^+ baryon at 1.5 and 1.75 GeV beam energies with and without imposing the relevant kinematical cuts on those parts of the sampled phase space where contribution from the main background sources, associated with the $\phi(1020)$, $\Lambda(1520)$ production as well as with the K^-p–rescattering in the final state, is expected to be dominant. We show that under chosen kinematics these distributions are still sensitive to the Θ^+ parity and, therefore, can be used as an important tool for identifying its parity.

[1]At excess energies above the $K^-\Theta^+$ threshold less than approximately 100 MeV as may be inferred from the arguments presented in the work [59], or, respectively, at the photon energies smaller than about 2 GeV if the reaction $\gamma n \to K^-\Theta^+$ takes place on a free target neutron being at rest.

2 Spectator model

Due to the high momentum transfer in the elementary process $\gamma n \to K^-\Theta^+$ near the threshold [2] and a large average separation of the neutron and proton in the deuteron we can analyze the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$ of our interest in the Impulse Approximation (IA) regime [79, 80]. In this regime the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$ reduces to the Θ^+ photoproduction off the neutron in the deuteron:

$$\gamma + n \to K^- + \Theta^+, \tag{1}$$

and its subsequent decay into the K^+n [3] :

$$\Theta^+ \to K^+n, \tag{2}$$

while the recoiling proton acts as a spectator (see, fig. 1). Considering that the width of Θ^+ is very small compared to its mass and using the results given in refs. [81, 82], we can represent in the IA the differential cross section for creation of the four–body final state K^-K^+np through the production/decay sequence (1, 2), taking place on a neutron embedded in a deuteron, as follows:

$$d\sigma^{(IA)}_{\gamma d\to K^-K^+np}(E_\gamma) = n_d(|\mathbf{p}_t|)\delta(\mathbf{p}_t+\mathbf{p}_s)d\mathbf{p}_t d\mathbf{p}_s \times \tag{3}$$

$$\times\frac{\pi}{I_2(s,m_K,m_{\Theta^+})}\frac{d\sigma_{\gamma n\to K^-\Theta^+}(s,\theta'_{K^-})}{d\mathbf{\Omega}'_{K^-}}\times$$

$$\times\delta(\mathbf{p}_\gamma+\mathbf{p}_t-\mathbf{p}_{K^-}-\mathbf{p}_{\Theta^+})\delta(E_\gamma+E_t-E_{K^-}-E_{\Theta^+})\frac{d\mathbf{p}_{K^-}}{E_{K^-}}\frac{d\mathbf{p}_{\Theta^+}}{E_{\Theta^+}}\times$$

$$\times\frac{d\Gamma_{\Theta^+\to K^+n}(m_{\Theta^+},\mathbf{p}_{\Theta^+})}{\Gamma_{\Theta^+}(m_{\Theta^+},\mathbf{p}_{\Theta^+})},$$

where

$$I_2(s,m_K,m_{\Theta^+}) = \frac{\pi}{\sqrt{s}}p'_{K^-}, \tag{4}$$

$$p'_{K^-} = \left|\mathbf{p}'_{K^-}\right| = \frac{1}{2\sqrt{s}}\lambda(s,m_K^2,m_{\Theta^+}^2), \tag{5}$$

$$\lambda(x,y,z) = \sqrt{\left[x-(\sqrt{y}+\sqrt{z})^2\right]\left[x-(\sqrt{y}-\sqrt{z})^2\right]}, \tag{6}$$

$$s = (E_\gamma+E_t)^2 - (\mathbf{p}_\gamma+\mathbf{p}_t)^2, \tag{7}$$

$$E_t = M_d - E_s, \;\; E_s = \sqrt{\mathbf{p}_s^2+m_p^2}, \tag{8}$$

$$E_{K^-} = \sqrt{\mathbf{p}_{K^-}^2+m_K^2}, \;\; E_{\Theta^+} = \sqrt{\mathbf{p}_{\Theta^+}^2+m_{\Theta^+}^2}; \tag{9}$$

and

$$d\Gamma_{\Theta^+\to K^+n}(m_{\Theta^+},\mathbf{p}_{\Theta^+}) = \frac{\left|M_{\Theta^+\to K^+n}\right|^2}{2E_{\Theta^+}}(2\pi)^4\delta(\mathbf{p}_{\Theta^+}-\mathbf{p}_{K^+}-\mathbf{p}_n)\times \tag{10}$$

[2]Which amounts to 1.73 GeV when the target neutron is at rest.

[3]Because in the photoproduction experiments [8, 10–12] the Θ^+ was observed in the K^+n decay mode, it is natural to consider this mode in the present work.

$$\times\delta(E_{\Theta^+}-E_{K^+}-E_n)\frac{d\mathbf{p}_{K^+}}{(2\pi)^3 2E_{K^+}}\frac{d\mathbf{p}_n}{(2\pi)^3 2E_n},$$

$$\Gamma_{\Theta^+}(m_{\Theta^+},\mathbf{p}_{\Theta^+})=\Gamma_{\Theta^+}(m_{\Theta^+})/\gamma_{\Theta^+},\ \ \gamma_{\Theta^+}=E_{\Theta^+}/m_{\Theta^+}, \tag{11}$$

$$E_{K^+}=\sqrt{\mathbf{p}_{K^+}^2+m_K^2},\ \ E_n=\sqrt{\mathbf{p}_n^2+m_n^2}. \tag{12}$$

Here, $(E_\gamma,\mathbf{p}_\gamma)$, $(E_t,\mathbf{p}_t)$, $(E_{\Theta^+},\mathbf{p}_{\Theta^+})$, $(E_{K^-},\mathbf{p}_{K^-})$, $(E_{K^+},\mathbf{p}_{K^+})$, $(E_n,\mathbf{p}_n)$, and $(E_s,\mathbf{p}_s)$ are the four–momenta in the lab (or deuteron rest) frame of the incoming photon, the struck target neutron, the intermediate Θ^+ resonance [4] , the outgoing K^-, K^+-mesons and the neutron, and the recoil proton, respectively; $d\sigma_{\gamma n\to K^-\Theta^+}(s,\theta^{'}_{K^-})/d\mathbf{\Omega}^{'}_{K^-}$ is the off–shell [5] differential cross section for the production of a K^--meson under the polar angle $\theta^{'}_{K^-}$ with the momentum $\mathbf{p}^{'}_{K^-}$ in reaction (1) in the γn c.m.s. ($\mathbf{\Omega}^{'}_{K^-}=\mathbf{p}^{'}_{K^-}/p^{'}_{K^-}$); $n_d(|\mathbf{p}_t|)$ is the nucleon momentum distribution in the deuteron normalized to unity; $m_p(m_n)$, m_K and M_d are the masses in free space of a proton (neutron), kaon and deuteron, respectively; m_{Θ^+} is the pole mass of the Θ^+ baryon ($m_{\Theta^+}=1.54$ GeV); $|M_{\Theta^+\to K^+n}|^2$ is the spin–averaged matrix element squared describing the decay (2); $\Gamma_{\Theta^+}(m_{\Theta^+})$ is the total width of the decay of Θ^+ in its rest frame, taken at the pole of the resonance.

Let us now specify the off–shell differential cross section $d\sigma_{\gamma n\to K^-\Theta^+}(s,\theta^{'}_{K^-})/d\mathbf{\Omega}^{'}_{K^-}$ for K^- production in the elementary process (1), entering into eq. (3). Following refs. [79–82], we assume that this cross section is equivalent to the respective on–shell cross section calculated for the off–shell kinematics of the reaction (1). The on–shell differential cross section for the reaction $\gamma n\to K^-\Theta^+$ has been calculated theoretically in refs. [58, 59] using both the respective hadronic model and the CGLN amplitudes. The results of the calculations show that this cross section in the threshold energy region, i.e. at $E_\gamma\le 2$ GeV, can be approximately parametrized by

$$\frac{d\sigma_{\gamma n\to K^-\Theta^+}(s,\theta^{'}_{K^-})}{d\mathbf{\Omega}^{'}_{K^-}}=\begin{cases}\frac{1}{4\pi}\sigma^{(+)}_{\gamma n\to K^-\Theta^+}(\sqrt{s}) & \text{for the positive } \Theta^+ \text{ parity,}\\[2ex] \frac{3}{8\pi}\sin^2\theta^{'}_{K^-}\sigma^{(-)}_{\gamma n\to K^-\Theta^+}(\sqrt{s}) & \text{for the negative } \Theta^+ \text{ parity.}\end{cases} \tag{13}$$

Here, $\sigma^{(+)}_{\gamma n\to K^-\Theta^+}(\sqrt{s})$ and $\sigma^{(-)}_{\gamma n\to K^-\Theta^+}(\sqrt{s})$ are the on–shell total cross sections of the elementary process $\gamma n\to K^-\Theta^+$ for the positive and negative Θ^+ parities, respectively. These cross sections have been also calculated in refs. [58, 59] and the results of calculations, taking into account that the s–wave (p–wave) antikaon production is expected [58, 59] near threshold when the Θ^+ has the positive (negative) parity, have been parametrized by us as follows:

$$\sigma^{(+)}_{\gamma n\to K^-\Theta^+}(\sqrt{s})=\frac{675p^{'}_{K^-}}{1+2p^{'2}_{K^-}}[\mathrm{nb}], \tag{14}$$

$$\sigma^{(-)}_{\gamma n\to K^-\Theta^+}(\sqrt{s})=\frac{595p^{'3}_{K^-}}{1+15p^{'3}_{K^-}}[\mathrm{nb}], \tag{15}$$

with $p^{'}_{K^-}$ denoting the K^- three–momentum in the γn c.m.s. measured in GeV/c. This momentum is defined above by eq. (5). An inspection of the formulas (14), (15)

[4]Which is assumed to be on–shell, since its width is very small compared to its mass.

[5]The struck target neutron is off–shell, see eq. (8).

leads, as is easy to see, to the conclusion that the total cross sections for the negative parity Θ^+ are approximately 10–100 times smaller than those for the positive parity one in the range of the photon energy 1.73 GeV $< E_\gamma <$ 3 GeV. Thus, for example, the positive and negative Θ^+ parity cases give the total cross sections of 100 nb and 2 nb, respectively, at $E_\gamma = 1.8$ GeV, whereas at $E_\gamma = 2.5$ GeV these cross sections, correspondingly, are 230 nb and 28 nb [6] .

The K^--meson production angle $\theta^{'}_{K^-}$ in the γn c.m.s., entering into eq. (13), is defined by

$$\cos\theta^{'}_{K^-} = \frac{\mathbf{p}^{'}_\gamma \mathbf{p}^{'}_{K^-}}{p^{'}_\gamma p^{'}_{K^-}}, \tag{16}$$

where $\mathbf{p}^{'}_\gamma$ denotes the three–momentum of an incident photon in this system. Writting the relativistic invariant $t = [(E_\gamma, \mathbf{p}_\gamma) - (E_{K^-}, \mathbf{p}_{K^-})]^2$ in the laboratory and in the γn c.m. systems and equating the results, we readily obtain

$$\cos\theta^{'}_{K^-} = \frac{p_\gamma p_{K^-}\cos\theta_{K^-} + (E^{'}_\gamma E^{'}_{K^-} - E_\gamma E_{K^-})}{p^{'}_\gamma p^{'}_{K^-}}. \tag{17}$$

In the above, θ_{K^-} is the angle between the momenta $\mathbf{p}_\gamma$ and $\mathbf{p}_{K^-}$ in the lab frame, while $E^{'}_\gamma$ and $E^{'}_{K^-}$ are the energies of the initial photon and outgoing antikaon in the γn c.m.s., respectively. These energies are given by

$$E^{'}_\gamma = p^{'}_\gamma = \frac{1}{2\sqrt{s}}\lambda(s, 0, E_t^2 - p_t^2), \tag{18}$$

$$E^{'}_{K^-} = \sqrt{p^{'2}_{K^-} + m_K^2}. \tag{19}$$

Consider now the spin–averaged matrix element squared $|M_{\Theta^+\to K^+n}|^2$ describing the decay $\Theta^+ \to K^+n$. Following the parity and angular momentum conservation laws, the decay amplitude $M_{\Theta^+\to K^+n}$ should exhibit a p– or s–wave behavior (for a spin–$\frac{1}{2}\Theta^+$) in the Θ^+ rest frame when the Θ^+ has the positive or negative parity, respectively. However, if the spin state of the outgoing neutron is not fixed, the difference between the angular distributions of the $\Theta^+ \to K^+n$ decay, corresponding to the positive and negative Θ^+ parity, disappears [65], which means that the spin–averaged matrix element squared $|M_{\Theta^+\to K^+n}|^2$ results in an isotropic angular distribution of this decay for both parities of Θ^+. By taking this fact into consideration as well as integrating eq. (10) over the momenta $\mathbf{p}_{K^+}$ and $\mathbf{p}_n$ in the Θ^+ rest frame, we can easily get the following relation between $|M_{\Theta^+\to K^+n}|^2$ and the partial width $\Gamma_{\Theta^+\to K^+n}(m_{\Theta^+})$ of the $\Theta^+ \to K^+n$ decay:

$$\frac{|M_{\Theta^+\to K^+n}|^2}{(2\pi)^2} = \frac{2m^2_{\Theta^+}}{\pi \overset{*}{p}_{K^+}}\Gamma_{\Theta^+\to K^+n}(m_{\Theta^+}), \tag{20}$$

where [7]

$$\overset{*}{p}_{K^+} = \frac{1}{2m_{\Theta^+}}\lambda(m^2_{\Theta^+}, m^2_K, m^2_n). \tag{21}$$

[6]It should be noted that these values are in disagreement with the results of the experiment [28]. In the light of these results the use of eqs. (14), (15) enables us to obtain an upper estimate of the strength of the respective antikaon angular distributions and has no influence on their shape of our main interest.

[7]Note that the K^+ momentum $\overset{*}{p}_{K^+}$ in the Θ^+ decay into K^+n in its rest frame, as is easy to calculate, is equal to 269.7 MeV/c.

By using the relation (20), one finds that the ratio $d\Gamma_{\Theta^+ \to K^+ n}(m_{\Theta^+}, \mathbf{p}_{\Theta^+})/\Gamma_{\Theta^+}(m_{\Theta^+}, \mathbf{p}_{\Theta^+})$, entering into eq. (3), reduces to a simpler form:

$$\frac{d\Gamma_{\Theta^+ \to K^+ n}(m_{\Theta^+}, \mathbf{p}_{\Theta^+})}{\Gamma_{\Theta^+}(m_{\Theta^+}, \mathbf{p}_{\Theta^+})} = \frac{m_{\Theta^+}}{\pi \overset{*}{p}_{K^+}} BR(\Theta^+ \to K^+ n)\delta(\mathbf{p}_{\Theta^+} - \mathbf{p}_{K^+} - \mathbf{p}_n) \times \quad (22)$$

$$\times \delta(E_{\Theta^+} - E_{K^+} - E_n)\frac{d\mathbf{p}_{K^+}}{2E_{K^+}}\frac{d\mathbf{p}_n}{2E_n},$$

where

$$BR(\Theta^+ \to K^+ n) = \Gamma_{\Theta^+ \to K^+ n}(m_{\Theta^+})/\Gamma_{\Theta^+}(m_{\Theta^+}). \quad (23)$$

According to [21, 83, 84], $BR(\Theta^+ \to K^+ n) = 1/2$ for both parities of Θ^+.

Before going to the next step, we discuss now the nucleon momentum distribution in the deuteron $n_d(p_t)$ [8] needed for our calculations. This momentum distribution has been calculated in [85], using the Paris potential [86, 87], and the results of calculations have been parametrized here by the simple analytical form (A1) (see also formula (23) in ref. [82]). This form has been employed in our calculations of the K^- production cross sections in the reaction $\gamma d \to K^- \Theta^+ p \to K^- K^+ np$ reported in the paper. In fig. 2 we present the momentum distribution of the proton–spectator $p_s^2 n_d(p_s)$ in this reaction (solid curve) calculated using the parametrization (A1) from [85] for $n_d(p_s)$. It is clearly seen that this distribution has a sharp peak with a maximum near 45 MeV/c and the long tail above 150 MeV/c.

Now, let us proceed to the identification of the kinematic regions where the reaction $\gamma d \to K^- K^+ np$, going via the production/decay sequence (1, 2), is expected to dominate over the non–resonant background [9] . It is natural to consider this reaction namely in these identified kinematic regions. According to [8, 10, 65, 66], the main contribution to the non–resonant background in the near–threshold region with $E_\gamma \leq 2$ GeV comes from the intermediate ϕ-meson and $\Lambda(1520)$-hyperon photoproduction:$\gamma N \to \phi N \to K^+ K^- N$ and $\gamma p \to K^+ \Lambda(1520) \to K^+ K^- p$. Thus, for example, our calculations [10] show that at $E_\gamma = 1.8$ GeV the $K^+ K^-$ invariant mass $M_{K^+K^-}$ in the process $\gamma n \to K^- \Theta^+ \to K^- K^+ n$ taking place on a free neutron being at rest is distributed in the region 1.0 GeV $\leq M_{K^+K^-} \leq$ 1.1 GeV. The narrow mass distribution of the ϕ concentrates largely in the region of the $K^+ K^-$ invariant masses 1.00 GeV $< M_{K^+K^-} <$ 1.04 GeV [8, 65] (the so–called "ϕ window") and, therefore, lies completely within the sampled kinematic region indicated above, which makes the ϕ-meson contribution to the respective data sample significant [8, 10, 65, 66]. In order to suppress this contribution and enhance signal to background ratio, the ϕ-mesons have to be removed from the data sample. In order to remove the ϕ-mesons, events with 1.00 GeV $< M_{K^+K^-} <$ 1.04 GeV have to be rejected [8, 65]. This means that we have to eliminate the phase space with the $K^+ K^-$ invariant mass from 1.00 to 1.04 GeV in our consideration of the reaction $\gamma d \to K^- \Theta^+ p \to K^- K^+ np$. To

[8] Or the momentum distribution $n_d(p_s)$ of the nucleon–spectator produced by the spectator mechanism in the reactions off the deuteron target nucleus.

[9] The reactions which contribute to the same final state $K^- K^+ np$ and do not proceed through the virtual Θ^+ state.

[10] Performed in line with the formulas (25)–(31) given below.

make this, we will multiply the differential cross section (3) by the "ϕ phase space eliminating" factor $Q(M_{K^+K^-})$ defined as:

$$Q(M_{K^+K^-}) = \begin{cases} 0 & \text{for } 1.00 \text{ GeV} < M_{K^+K^-} < 1.04 \text{ GeV}, \\ \\ 1 & \text{otherwise.} \end{cases} \quad (24)$$

Before going further, one has to evaluate the invariant mass $M_{K^+K^-}$ of a K^+K^-–pair produced in the production/decay sequence (1, 2). In order to evaluate this quantity it is more convenient to put ourselves in the γn c.m.s. Then, the invariant $M^2_{K^+K^-}$ can be expressed through the energies and momenta of the K^+ and the K^-, $E^{'}_{K^+}$, $\mathbf{p}^{'}_{K^+}$ and $E^{'}_{K^-}$, $\mathbf{p}^{'}_{K^-}$, in this system in the following way:

$$M^2_{K^+K^-} = \left(E^{'}_{K^+} + E^{'}_{K^-}\right)^2 - \left(\mathbf{p}^{'}_{K^+} + \mathbf{p}^{'}_{K^-}\right)^2 = 2m^2_K + 2E^{'}_{K^+}E^{'}_{K^-} - 2\mathbf{p}^{'}_{K^+}\mathbf{p}^{'}_{K^-}, \quad (25)$$

where

$$E^{'}_{K^+} = \sqrt{\mathbf{p}^{'2}_{K^+} + m^2_K}, \quad (26)$$

and the quantities $p^{'}_{K^-}$ and $E^{'}_{K^-}$ are defined above by eqs. (5) and (19), respectively. Taking into account that the kaon momentum $\mathbf{p}^{'}_{K^+}$ can be expressed via its momentum $\overset{*}{\mathbf{p}}_{K^+}$ in the Θ^+ rest frame and the Θ^+ momentum $\mathbf{p}^{'}_{\Theta^+}$ in the γn c.m.s. as [88]

$$\mathbf{p}^{'}_{K^+} = \frac{p^{'}_{\Theta^+} \overset{*}{E}_{K^+}}{m_{\Theta^+}}\mathbf{n}_{\Theta^+} + \overset{*}{p}_{K^+} \left\{\mathbf{n}^*_{K^+} + (\gamma^{'}_{\Theta^+} - 1)\cos\theta^*_{K^+}\mathbf{n}_{\Theta^+}\right\}, \quad (27)$$

where

$$\overset{*}{E}_{K^+} = \sqrt{\overset{*}{p}{}^2_{K^+} + m^2_K}, \gamma^{'}_{\Theta^+} = E^{'}_{\Theta^+}/m_{\Theta^+}, E^{'}_{\Theta^+} = \sqrt{\mathbf{p}^{'2}_{\Theta^+} + m^2_{\Theta^+}}, p^{'}_{\Theta^+} = p^{'}_{K^-}, \quad (28)$$

$$\mathbf{n}_{\Theta^+} = \mathbf{p}^{'}_{\Theta^+}/p^{'}_{\Theta^+}, \ \mathbf{n}^*_{K^+} = \overset{*}{\mathbf{p}}_{K^+}/\overset{*}{p}_{K^+}, \ \cos\theta^*_{K^+} = \mathbf{n}^*_{K^+}\mathbf{n}_{\Theta^+}, \quad (29)$$

we easily get that:

$$\mathbf{p}^{'2}_{K^+} = \left(\frac{p^{'}_{\Theta^+} \overset{*}{E}_{K^+}}{m_{\Theta^+}}\right)^2 + \frac{2\overset{*}{E}_{K^+} E^{'}_{\Theta^+} \overset{*}{p}_{K^+} p^{'}_{\Theta^+}}{m^2_{\Theta^+}}\cos\theta^*_{K^+} + \quad (30)$$

$$+ \overset{*}{p}{}^2_{K^+}\left\{1 + (\gamma^{'2}_{\Theta^+} - 1)\cos^2\theta^*_{K^+}\right\},$$

$$2\mathbf{p}^{'}_{K^+}\mathbf{p}^{'}_{K^-} = -\frac{2p^{'}_{K^-}}{m_{\Theta^+}}\left[p^{'}_{\Theta^+}\overset{*}{E}_{K^+} + \overset{*}{p}_{K^+} E^{'}_{\Theta^+}\cos\theta^*_{K^+}\right]. \quad (31)$$

The K^+ momentum $\overset{*}{p}_{K^+}$ in the Θ^+ rest frame, entering into eqs. (27)–(31), is defined above by the (21). It should be emphasized that, according to (5), (19), (25)–(31), the invariant mass $M_{K^+K^-}$ of interest depends only on the cosine of the K^+ decay angle $\theta^*_{K^+}$ in the Θ^+ rest system and the squared invariant energy s available in the first–chance γn–collision, which simplifies the calculations presented below.

Similarly, our calculations [11] show that at $E_\gamma = 1.8$ GeV the invariant mass M_{K^-p} of the K^-p system in the reaction $\gamma d \to K^-\Theta^+p$ is distributed in the region

[11]Carried out in line with the following absolute limits for the invariant mass M_{K^-p} of interest: $m_K + m_p \le M_{K^-p} \le \sqrt{(E_\gamma + M_d)^2 - \mathbf{p}^2_\gamma} - m_{\Theta^+}$.

1.432 GeV $\le M_{K^-p} \le$ 1.665 GeV which straddles the $\Lambda(1520)$ mass, since the peak corresponding to the $\Lambda(1520)$ lies basically [10] in the region of the K^-p invariant masses 1.485 GeV $< M_{K^-p} <$ 1.551 GeV. This makes the $\Lambda(1520)$ contribution to the same final state of our interest significant [8, 10, 66]. To reduce this contribution and, respectively, to improve signal to background ratio, the $\Lambda(1520)$ resonance has to be removed from the data sample by rejecting events with [10] 1.485 GeV $< M_{K^-p} <$ 1.551 GeV. This means that we have to eliminate also the phase space with the K^-p invariant mass from 1.485 to 1.551 GeV in our study of the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$.To do this, we will also multiply the differential cross section (3) by the "$\Lambda(1520)$ phase space eliminating" factor $Q(M_{K^-p})$. This factor is defined in the following way:

$$Q(M_{K^-p}) = \begin{cases} 0 & \text{for } 1.485 \text{ GeV} < M_{K^-p} < 1.551 \text{ GeV}, \\ \\ 1 & \text{otherwise.} \end{cases} \tag{32}$$

The invariant mass squared $M^2_{K^-p}$ can be obtained in a straightforward manner, and the result is

$$M^2_{K^-p} = \left(E_{K^-} + \sqrt{(-\mathbf{p}_t)^2 + m_p^2}\right)^2 - (\mathbf{p}_{K^-} - \mathbf{p}_t)^2 = \tag{33}$$

$$= m_K^2 + m_p^2 + 2E_{K^-}\sqrt{(-\mathbf{p}_t)^2 + m_p^2} + 2p_{K^-}p_t\cos\theta_{\mathbf{p}_t\mathbf{p}_{K^-}}$$

with $\theta_{\mathbf{p}_t\mathbf{p}_{K^-}}$ being the angle between the momenta $\mathbf{p}_t$ and $\mathbf{p}_{K^-}$ in the lab frame. This angle is related to the angles between $\mathbf{p}_\gamma$ and $\mathbf{p}_t$ (θ_t), $\mathbf{p}_\gamma$ and $\mathbf{p}_{K^-}$ (θ_{K^-}) and to the azimuthal angles φ_t of $\mathbf{p}_t$, φ_{K^-} of $\mathbf{p}_{K^-}$ by the trigonometric relation

$$\cos\theta_{\mathbf{p}_t\mathbf{p}_{K^-}} = \cos\theta_{K^-}\cos\theta_t + \sin\theta_{K^-}\sin\theta_t\cos(\varphi_t - \varphi_{K^-}). \tag{34}$$

There is yet another background source, if we want to look at the antikaon angular distributions from primary production process (1). This source of background is related to the possible rescattering [12] of the produced K^--meson on the proton in the final state (see fig. 3). Such rescattering may distort the angular distributions of antikaons produced in γd interactions through the primary photon–induced reaction channel $\gamma n \to K^-\Theta^+$ of interest (see fig. 1). Therefore, we also need to specify the kinematic region, in addition to those specified before, where the K^-p–rescattering is expected to be negligible. This region has to be taken into consideration as well in the subsequent calculations of the K^- angular distributions from the primary reaction channel (1). The effects of rescattering on the recoil nucleon in hadron– and photon–deuteron interactions have been discussed previously (see, e.g., refs. [89–98] and references therein). Following [89, 90], the ratio of the moduli of the amplitudes corresponding to the diagrams of fig. 3 and fig. 1 ($M^{(FSI)}$ and $M^{(IA)}$, respectively) can be estimated using the relation

$$\frac{|M^{(FSI)}|}{|M^{(IA)}|} \approx \frac{|f_{K^-p\to K^-p}|}{4\pi R_d}\frac{1}{q_{K^-p}R_d}\frac{\varphi_d(0)}{\varphi_d(p_s)}. \tag{35}$$

Here, $f_{K^-p\to K^-p}$ is the elastic K^-p scattering amplitude normalized on the K^- differential cross section $d\sigma_{K^-p\to K^-p}/d\mathbf{\Omega}_{c.m.s.}$ in the K^-p c.m.s. by $|f_{K^-p\to K^-p}|^2 =$

[12] Or final–state interaction (FSI).

$d\sigma_{K^-p\to K^-p}/d\mathbf{\Omega}_{c.m.s.}$; q_{K^-p} is the relative momentum of the intermediate K^--meson and the spectator proton; R_d is the average internucleon distance inside the deuteron; φ_d is the deuteron wave function in momentum space. The K^-p rescattering plays a significant role in the case of the relative momenta q_{K^-p} falling in the low–momentum region $q_{K^-p} < 100$ MeV/c where the K^-p elastic cross section $\sigma_{K^-p\to K^-p}$ is large ($\sigma_{K^-p\to K^-p} > (80-100)$ mb [99–101]). Therefore, to reduce this rescattering we will restrict ourselves in the following to the case of relative momenta $q_{K^-p} \geq 100$ MeV/c [13] . Then, employing, e.g., the Hulthen wave function [14] [102] for φ_d to estimate the ratio (35) and assuming that $|f_{K^-p\to K^-p}| \approx \sqrt{80\text{mb}/4\pi}$ here, one obtaines that for $q_{K^-p} \geq 100$ MeV/c (or for $M_{K^-p} \geq 1.447$ GeV) the contribution from the diagram of fig. 3 is suppressed at least at the recoil proton momenta of $p_s < 280$ MeV/c. Hence, the spectator mechanism of fig. 1 gives the dominant contribution to the Θ^+ photoproduction from the neutron in the deuteron at small values of the spectator proton momentum p_s.

So, the above considerations require that the K^-p invariant mass must be greater than 1.447 GeV and the recoil proton momentum must be smaller than 280 MeV/c. To fulfil these requirements, we will multiply the differential cross section (3) by one more "K^-p phase space terminating" factor $Q(M_{K^-p}, p_s)$. This factor is given by:

$$Q(M_{K^-p}, p_s) = \theta(M_{K^-p} - M_{cut})\theta(p_{cut} - p_s), \tag{36}$$

where $M_{cut} = 1.447$ GeV, $p_{cut} = 280$ MeV/c and $\theta(x)$ is the standard step function.

Finally, by combining (3), (24), (32) and (36), we get within the IA the following expression for the differential cross section of the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$ over all the physical variables, which includes the phase space cuts we introduced:

$$d\sigma_{\gamma d\to K^-K^+np}(E_\gamma) = d\sigma^{(IA)}_{\gamma d\to K^-K^+np}(E_\gamma)Q(M_{K^+K^-})Q(M_{K^-p})Q(M_{K^-p}, p_s). \tag{37}$$

Integrating eq. (37) over the available phase space with accounting for (22), we get after some algebra the exclusive differential cross section of eq. (37) in the laboratory frame of physical (and practical) interest, where the final antikaon is detected without analyzing its energy for fixed three–momentum of the proton–spectator:

$$\frac{d\sigma_{\gamma d\to K^-K^+np}(E_\gamma)}{d\mathbf{\Omega}_{K^-}dp_sd\mathbf{\Omega}_s} = p_s^2 n_d(p_s)\theta(v^{'}_{K^-} - v_c)\theta(p_{cut} - p_s)\times \tag{38}$$

$$\times\frac{p^{(1)2}_{K^-}}{p^{'}_{K^-}\sqrt{p^{'2}_{K^-} - \gamma_c^2 v_c^2 m_K^2 \sin^2\theta^c_{K^-}}}\frac{d\sigma_{\gamma n\to K^-\Theta^+}[s, \theta^{'}_{K^-}(p^{(1)}_{K^-})]}{d\mathbf{\Omega}^{'}_{K^-}}\times$$

$$\times Q[M_{K^-p}(p^{(1)}_{K^-})]\theta[M_{K^-p}(p^{(1)}_{K^-}) - M_{cut}]\times$$

$$\times\frac{1}{2}BR(\Theta^+ \to K^+n)\int\limits_{-1}^{1} Q[M_{K^+K^-}(p_t, \theta_t, \cos\theta^*_{K^+})]d\cos\theta^*_{K^+}+$$

$$+p_s^2 n_d(p_s)\theta(v_c - v^{'}_{K^-})\theta(p_{cut} - p_s)\times$$

[13]Accounting for the relation $q_{K^-p} = \frac{1}{2M_{K^-p}}\lambda(M^2_{K^-p}, m_K^2, m_p^2)$, we can easily obtain that this corresponds to the region of the K^-p invariant masses $M_{K^-p} \geq 1.447$ GeV.

[14]The quantity R_d for this function is equal to 3.1 fm.

$$\times \sum_{i=1}^{2} \frac{p_{K^-}^{(i)2}}{p'_{K^-}\sqrt{p'^2_{K^-} - \gamma_c^2 v_c^2 m_K^2 \sin^2\theta^c_{K^-}}} \frac{d\sigma_{\gamma n \to K^-\Theta^+}[s, \theta'_{K^-}(p^{(i)}_{K^-})]}{d\mathbf{\Omega}'_{K^-}} \times$$

$$\times Q[M_{K^-p}(p^{(i)}_{K^-})]\theta[M_{K^-p}(p^{(i)}_{K^-}) - M_{cut}]\times$$

$$\times \frac{1}{2} BR(\Theta^+ \to K^+ n) \int\limits_{-1}^{1} Q[M_{K^+K^-}(p_t, \theta_t, \cos\theta^*_{K^+})] d\cos\theta^*_{K^+},$$

where

$$\mathbf{\Omega}_{K^-} = \mathbf{p}_{K^-}/p_{K^-},\ \mathbf{\Omega}_s = \mathbf{p}_s/p_s,\ v'_{K^-} = p'_{K^-}/E'_{K^-}, \qquad (39)$$
$$v_c = |\mathbf{v}_c|,\ \mathbf{v}_c = \frac{\mathbf{p}_\gamma + \mathbf{p}_t}{E_\gamma + E_t},\ \gamma_c = \frac{1}{\sqrt{1-v_c^2}};$$

$$\cos\theta^c_{K^-} = \frac{\mathbf{p}_{K^-}\mathbf{v}_c}{p_{K^-}v_c} = \frac{p_\gamma \cos\theta_{K^-} + p_t \cos\theta_{\mathbf{p}_t\mathbf{p}_{K^-}}}{v_c(E_\gamma + E_t)},\ \mathbf{p}_t = -\mathbf{p}_s \qquad (40)$$

and

$$p^{(1)}_{K^-} = \frac{p'_{K^-}(v_c/v'_{K^-})\cos\theta^c_{K^-} + \sqrt{p'^2_{K^-} - \gamma_c^2 v_c^2 m_K^2 \sin^2\theta^c_{K^-}}}{\gamma_c(1 - v_c^2\cos^2\theta^c_{K^-})}\ for\ v'_{K^-} > v_c, \qquad (41)$$

$$p^{(1,2)}_{K^-} = \frac{p'_{K^-}(v_c/v'_{K^-})\cos\theta^c_{K^-} \pm \sqrt{p'^2_{K^-} - \gamma_c^2 v_c^2 m_K^2 \sin^2\theta^c_{K^-}}}{\gamma_c(1 - v_c^2\cos^2\theta^c_{K^-})}\ for\ v'_{K^-} \le v_c. \qquad (42)$$

The quantity $\cos\theta_{\mathbf{p}_t\mathbf{p}_{K^-}}$, entering into eq. (40), is defined above by the (34). It is worth noting that, as is evident from eqs. (41), (42), in the case when the K^--meson velocity v'_{K^-} in the γn c.m.s. is greater than the velocity v_c of this system in the lab frame ($v'_{K^-} > v_c$) the polar K^- production angle $\theta^c_{K^-}$ varies without restriction between 0 and π, otherwise ($v'_{K^-} \le v_c$) it lies in the interval $(0, \arcsin(p'_{K^-}/\gamma_c v_c m_K))$. Thus, for instance, simple calculations show that the maximal value of the K^--meson production angle θ_{K^-} in the lab system in the reaction $\gamma n \to K^-\Theta^+$ taking place on a free neutron being at rest [15] at $E_\gamma = 1.8$ GeV amounts approximately to 21^0, i.e., in the threshold energy region antikaons are mainly emitted in this reaction in forward directions (see, also, figs. 4–8 given below). Further observables of our interest for the exclusive $d(\gamma, K^-p)K^+n$ and inclusive $d(\gamma, K^-)K^+np$ processes, proceeding through the intermediate Θ^+ state, are the K^--meson angular distributions, respectively, for fixed and non–fixed solid angle of the proton–spectator. Because of eq. (38), they are given by:

$$\frac{d\sigma_{\gamma d \to K^-K^+np}(E_\gamma)}{d\mathbf{\Omega}_{K^-}d\mathbf{\Omega}_s} = \int dp_s \frac{d\sigma_{\gamma d \to K^-K^+np}(E_\gamma)}{d\mathbf{\Omega}_{K^-}dp_s d\mathbf{\Omega}_s}, \qquad (43)$$

$$\frac{d\sigma_{\gamma d \to K^-K^+np}(E_\gamma)}{d\mathbf{\Omega}_{K^-}} = \int\int dp_s d\mathbf{\Omega}_s \frac{d\sigma_{\gamma d \to K^-K^+np}(E_\gamma)}{d\mathbf{\Omega}_{K^-}dp_s d\mathbf{\Omega}_s}. \qquad (44)$$

Let us discuss now the results of our calculations in the framework of the approach outlined above.

[15] In this case, as is easy to see, $\theta_{K^-} = \theta^c_{K^-}$.

3 Results

At first, we consider the exclusive differential cross section (38) for the process $d(\gamma, K^-p)K^+n$ proceeding through the intermediate Θ^+ state. There are many options to display the information contained in this cross section. In particular, in fig. 4 we show the exclusive K^--meson differential cross sections in the lab frame for the proton–spectator emerging in the direction of the incoming photon (i.e. at $\mathbf{\Omega_s} = \mathbf{\Omega}_\gamma$, where $\mathbf{\Omega}_\gamma = \mathbf{p}_\gamma/p_\gamma$) with momentum of 270 MeV/c calculated by eq. (38) for different assumptions concerning the parity of the Θ^+ state and the availability of the limitations (32), (36) we introduced on the phase space of the K^-p system at beam energy of 1.5 GeV. The same as in fig. 4 but calculated for the photon energy of 1.75 GeV and the proton–spectator momentum of 45 MeV/c is shown in fig. 5. A choice of these two options for the incident energy and the three–momentum of the proton–spectator has been particularly motivated by the fact that the excess energies above the $K^-\Theta^+$ threshold, corresponding to both options (26 and 42 MeV, respectively), fall in the near–threshold energy region of interest ($\leq 100\ MeV$). Under this choice, the respective antikaon velocities in the γn c.m.s. turn out to be smaller than the ones of this system in the lab frame. This means that in the chosen kinematical conditions only the second term in eq. (38) plays a role and, therefore, the K^--meson production angle θ_{K^-} in the lab system must be limited [16] . Our calculations show that the maximal value of this angle amounts to 28.7^0 and 26.3^0 for $E_\gamma = 1.5$ GeV, $p_s = 270$ MeV/c, $\mathbf{\Omega_s} = \mathbf{\Omega}_\gamma$ and $E_\gamma = 1.75$ GeV, $p_s = 45$ MeV/c, $\mathbf{\Omega_s} = \mathbf{\Omega}_\gamma$, respectively, which is reflected in the results we have exhibited in figs. 4 and 5. Looking at these figures, one can see that there are a clear differences between the antikaon angular distributions calculated for different Θ^+ parities and the same assumptions concerning the availability of the limitations on the phase space of the K^-p system (between dashed and solid, double–dot–dashed and dot–dashed lines). Namely, in the case of negative–parity Θ^+, the distributions (dashed and double–dot–dashed curves) are strongly suppressed at forward angles $\theta_{K^-} \leq 15^0$, whereas in the case of positive–parity Θ^+, the ones (solid and dot–dashed lines) are flat at these angles. Moreover, although at larger angles the respective differential cross sections belonging to the calculations for different Θ^+ parities have a similar shapes (compare dashed and solid, double–dot–dashed and dot–dashed lines in figs. 4 and 5), their strengths here for the negative–parity Θ^+ are about forty times smaller than those for the positive–parity one. Comparing the curves, corresponding to the calculations for the same Θ^+ parities with and without placing the cuts under consideration on the phase space of the K^-p system (solid and dot–dashed, dashed and double–dot–dashed lines, respectively), one can also see that these cuts only slightly reduce the strengths of the cross sections practically at all allowed angles in the case of the kinematics of fig. 4, while in the kinematical conditions of fig. 5 they decrease the cross sections only in small region of angles near the maximal K^--meson production angle [17] . This means

[16] Since in the chosen kinematics $\theta_{K^-} = \theta^c_{K^-}$ and the angle $\theta^c_{K^-}$, defined above by eq. (40), is limited in line with the text given just below the eq. (42).

[17] It is interesting to note that placing the cut (24) on the phase space of the K^+K^- system results in reduction of the antikaon yield from the process (1) by the factors of about 1.7 and 1.5 in the kinematical conditions, respectively, of fig. 4 and fig. 5. This means that about 40% and 30% of the total K^+K^- phase space are eliminated due to the cut (24), correspondingly, in the former and the latter cases and, therefore, the larger part of this space is free from the ϕ-meson background.

that the main strengths of the exclusive K^--meson differential cross sections under consideration concentrate in those parts of the sampled phase space where contribution from the background sources, associated both with the $\Lambda(1520)$ production and the K^-p–FSI effects, is expected to be negligible in the chosen kinematics. So, the foregoing shows that the observation of the exclusive antikaon angular distributions from the process $d(\gamma, K^-p)K^+n$ proceeding via the intermediate Θ^+ state near the threshold, like those just considered, can serve as an important tool to distinguish the parity of the Θ^+ baryon.

Let us concentrate now on the exclusive differential cross section (43) for the process $d(\gamma, K^-p)K^+n$ going through the virtual Θ^+ state. In fig. 6 we show the exclusive K^--meson differential cross sections in the lab frame for the proton–spectator emerging in the direction of the incoming photon calculated by eq. (43) with allowance for the same scenarios for the Θ^+ parity and the availability of the limitations on the phase space of the K^-p system as in the preceding case at incident energy of 1.5 GeV. It can be seen that here also there are a distinct differences between the respective negative–parity Θ^+ and the positive–parity Θ^+ results analogous to those observed previously. Namely, the calculations including negative–parity Θ^+ lie considerably lower the positive–parity Θ^+ results and, furthermore, their strengths are substantially suppressed at forward angles $\theta_{K^-} \le 15^0$, while the positive–parity Θ^+ results are basically constant at these angles. On the other hand, as shown in fig. 6, the differences between the calculations for the same Θ^+ parities with and without placing the cuts on the phase space of the K^-p system are small (cf. figs. 4 and 5), which means that the main strengths of the exclusive antikaon differential cross sections considered here lie in those parts of the sampled phase space where contribution from the background sources, associated with the $\Lambda(1520)$ production and the K^-p-rescattering in the final state, is expected to be negligible in the chosen kinematics. Therefore, the preceding gives the opportunity to determine the Θ^+ parity experimentally also by measuring the exclusive antikaon angular distribution from the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$, like that just considered, in the threshold energy region.

Finally, let us focus on the inclusive differential cross section (44) for the process $d(\gamma, K^-)K^+np$ proceeding through the intermediate Θ^+ state. In fig. 7 we show the inclusive K^--meson differential cross sections in the lab frame calculated by eq. (44) with employing the same scenarios for the parity of the Θ^+ pentaquark and the availability of the limitations on the phase space of the K^-p system as those of figs. 4, 5, 6 at the photon energy of 1.5 GeV. The same as in fig. 7 but calculated for the photon energy of 1.75 GeV is shown in fig. 8. One can see that the distinctions between the corresponding negative–parity Θ^+ and the positive–parity Θ^+ calculations are quite clear both for 1.5 and 1.75 GeV initial energies and analogous to those observed before. In particular, the cross sections calculated assuming that the Θ^+ has negative parity also are much suppressed at forward angles $\theta_{K^-} \le 15^0$, while the ones obtained supposing that the Θ^+ has positive parity, as in the preceding cases, are practically constant at these angles. Furthermore, although at larger angles [18] the respective antikaon angular distributions belonging to the calculations for different Θ^+ parities also have a similar shapes (compare dashed and solid, double–dot–dashed and dot–dashed curves in figs. 7 and 8), their strengths here for the negative–parity Θ^+ are

[18]Restricted at $E_\gamma = 1.5$ GeV as shown in fig. 7.

significantly reduced compared to those for the positive–parity one (cf. figs. 4, 5, 6). On the other hand, the differences between the calculations for the same Θ^+ parities with and without placing the cuts on the phase space of the K^-p system, as in the preceding cases, are largely insignificant, which means that also the main strengths of the inclusive K^--meson differential cross sections under consideration concentrate in those parts of the sampled phase space where contribution from the background sources, associated with the $\Lambda(1520)$ production and the K^-p–FSI effects, is expected to be negligible in the chosen kinematics. Therefore, the foregoing shows that the inclusive antikaon angular distribution from the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$ near the threshold also can be useful to help determine the parity of the Θ^+ pentaquark.

Taking into account the above considerations, we come to the conclusion that both the exclusive and inclusive K^--meson laboratory differential cross sections for the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$ near the threshold may be an important tool to determine the parity of the Θ^+ baryon. These observables might be measured on modern experimental facilities such as SPring–8, JLab, ELSA and ESRF.

4 Conclusions

In this paper we have investigated in a spectator model the possibility of determining the parity of the Θ^+ pentaquark from the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$ near the threshold. The elementary Θ^+ production process included in our study is $\gamma n \to K^-\Theta^+$. Taking into account the fact, established by the authors of refs. [58, 59], that the free c.m.s. differential cross section for this elementary process shows a clear distinction between the two opposite parities of the Θ^+ baryon close to the threshold and using their predictions for this cross section, we have calculated the exclusive and inclusive laboratory angular distributions of K^--mesons produced through this process, taking place on the moving neutron in the deuteron, for two possible parity states of the Θ^+ resonance at 1.5 and 1.75 GeV beam energies with and without placing the relevant kinematical cuts on those parts of the sampled phase space where contribution from the main background sources, associated with the $\phi(1020)$, $\Lambda(1520)$ production as well as with the K^-p–FSI effects, is expected to be dominant. We have shown that these cuts play an insignificant role in the chosen kinematics, namely, they only slightly reduce the antikaon angular distributions of interest, which means that, in the chosen kinematical conditions, the main strengths of these distributions concentrate in those parts of the sampled phase space where the non–resonant background is expected to be negligible. On the other hand, the calculated K^--meson angular distributions were found to be strongly sensitive to the Θ^+ parity. We, therefore, come to the conclusion that the observation of the exclusive and inclusive antikaon angular distributions from the reaction $\gamma d \to K^-\Theta^+p \to K^-K^+np$ near the threshold can serve as an important tool to distinguish the parity of the Θ^+ pentaquark. Such observation might be conducted at current experimental facilities.

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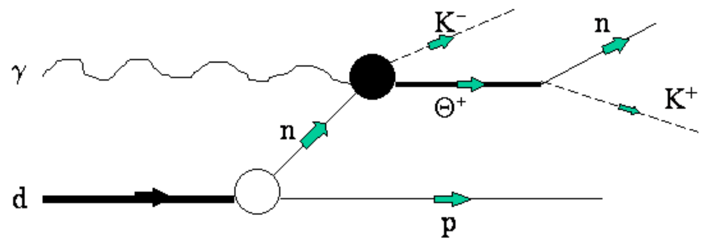

Figure 1: Diagrammatic representation of Θ^+ photoproduction from the deuteron within the Impulse Approximation (the Spectator mechanism).

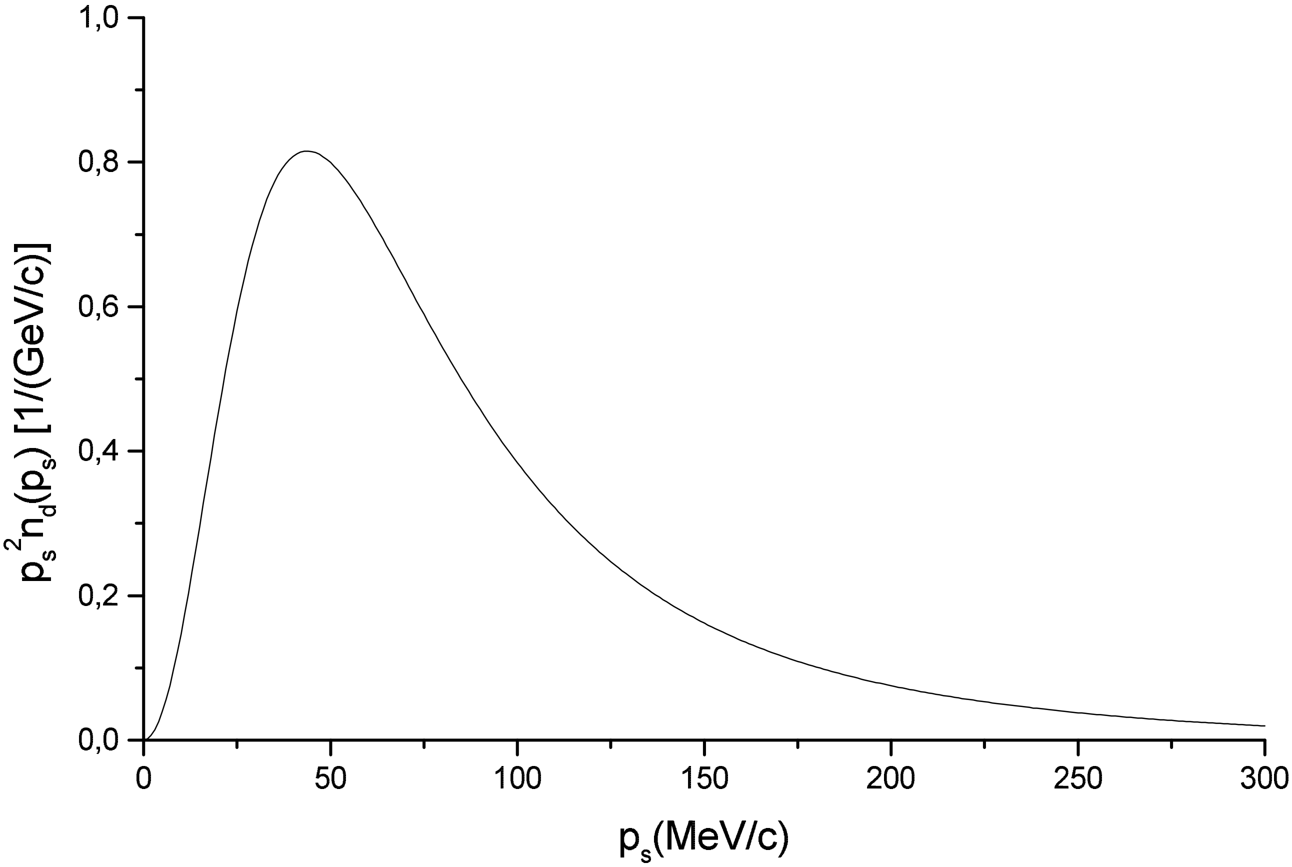

Figure 2: Momentum distribution of proton–spectator in the reaction $\gamma d \to K^- \Theta^+ p \to K^- K^+ n p$.

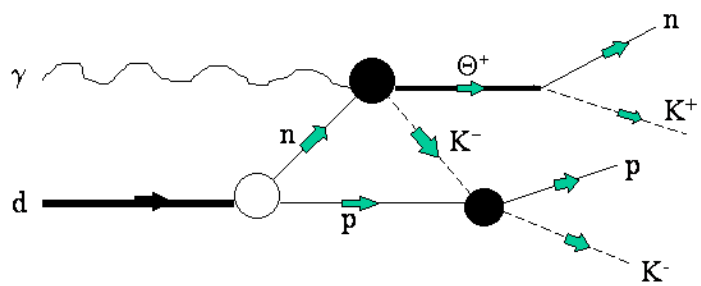

Figure 3: Diagrammatic representation of Θ^+ photoproduction from the deuteron including K^-p-rescattering in the final state.

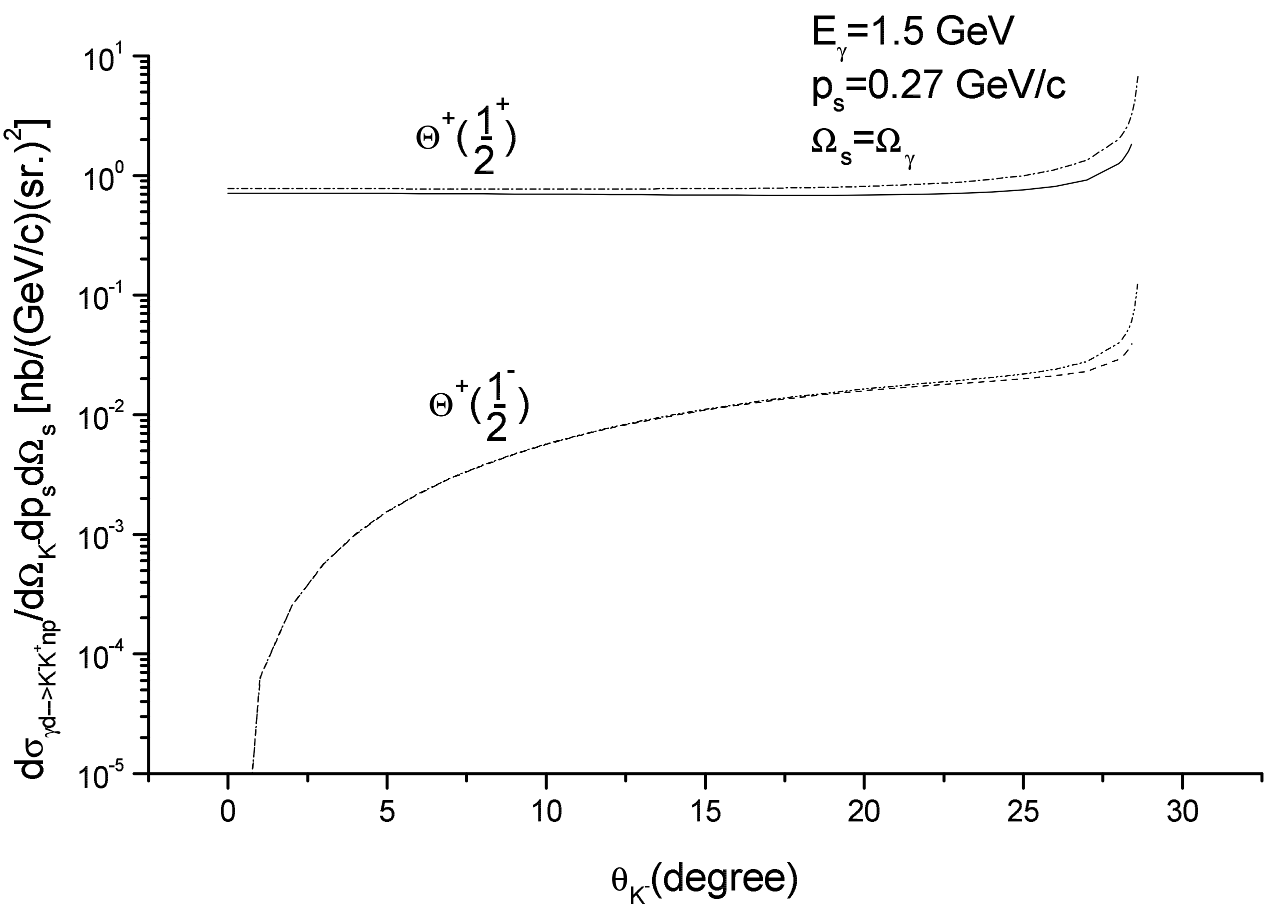

Figure 4: The exclusive K^--meson differential cross sections for the process $d(\gamma, K^-p)K^+n$ proceeding through the intermediate Θ^+ state at initial energy of 1.5 GeV with the proton–spectator emitted in the direction of an incident photon with momentum of 270 MeV/c as functions of the K^- production angle in the nuclear lab frame. The solid and dot–dashed (dashed and double–dot–dashed) lines are calculations for positive (negative) Θ^+ parity, respectively, with and without taking into account the limitations under consideration on the phase space of the K^-p system. The limitation we introduced on the phase space of the K^+K^- system is included in all calculations.

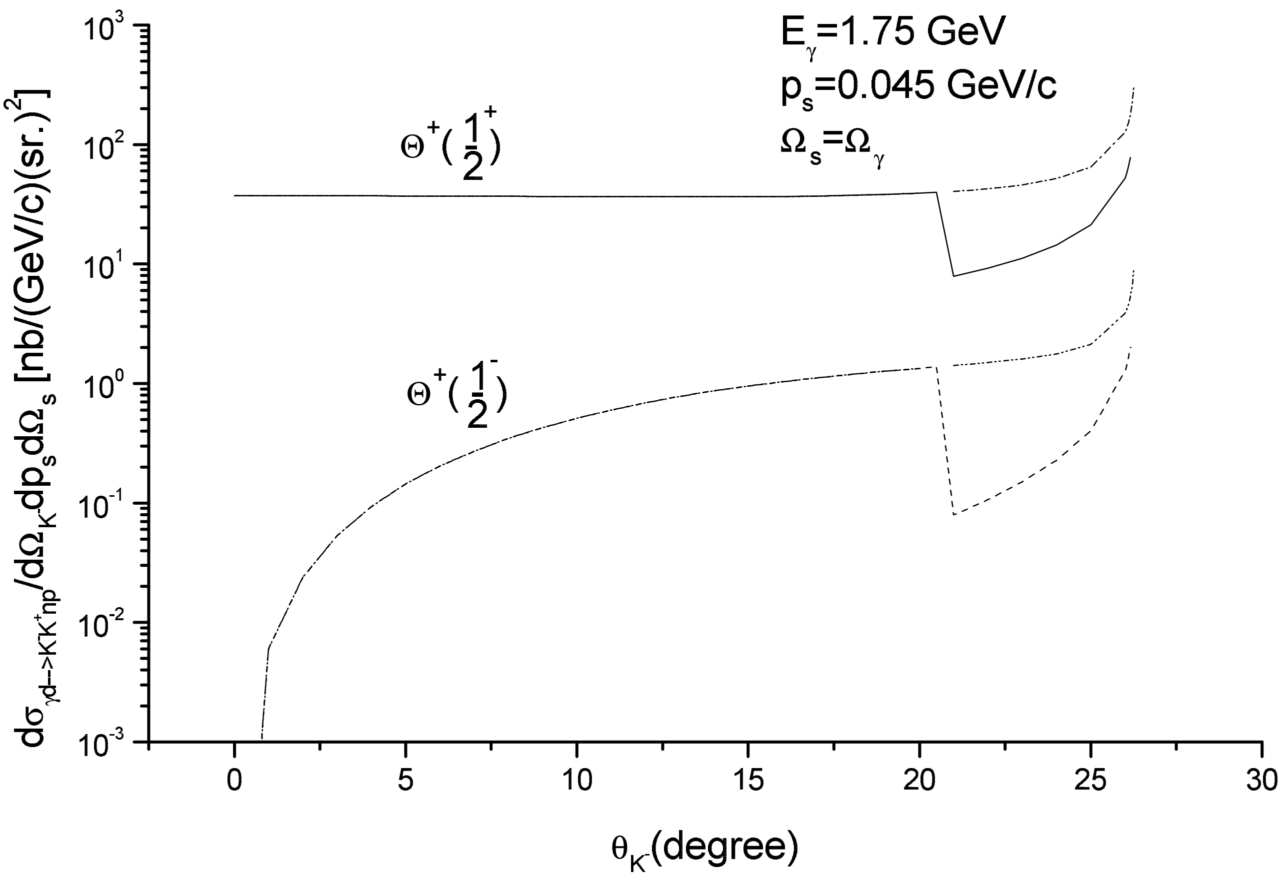

Figure 5: The same as in fig. 4 but for 1.75 GeV beam energy and 45 MeV/c proton–spectator momentum.

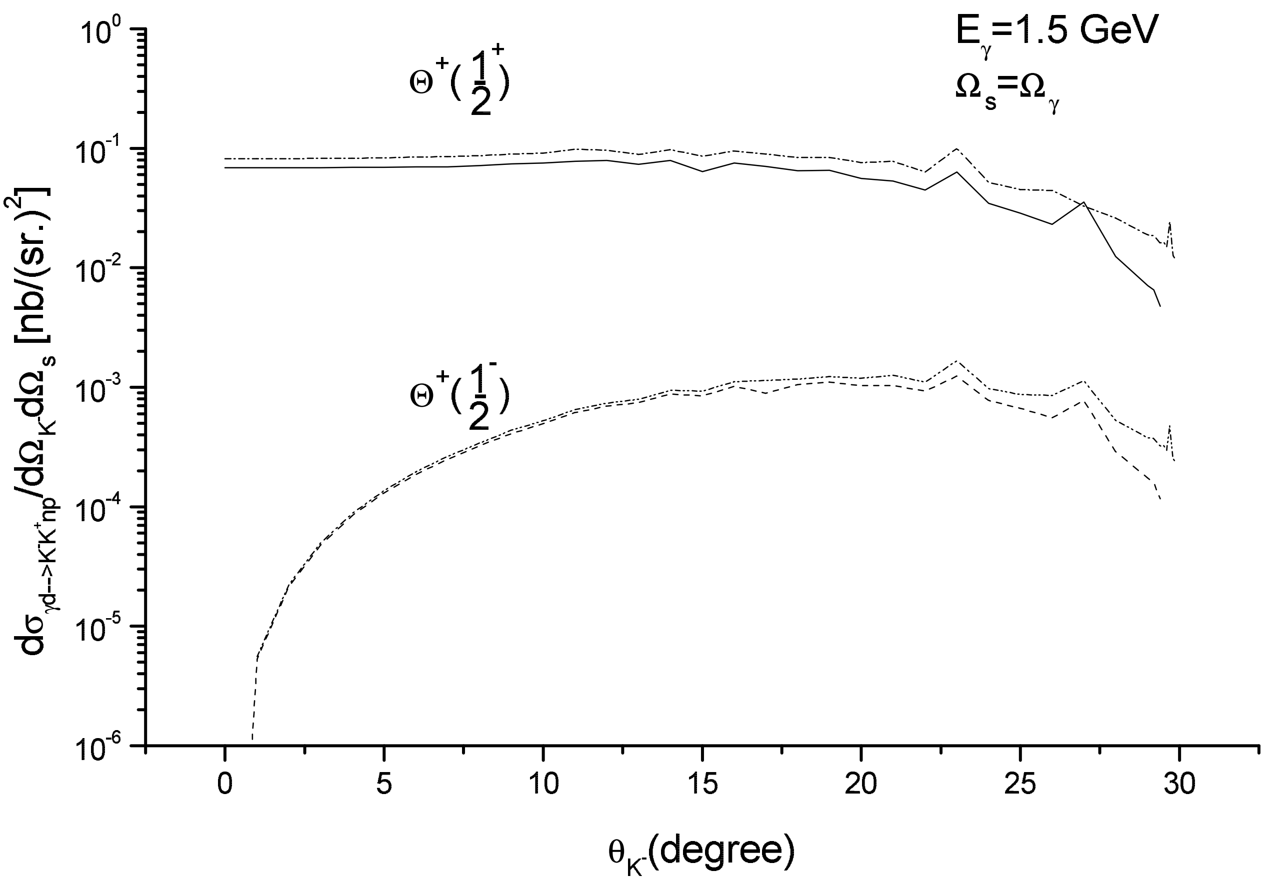

Figure 6: The exclusive K^--meson differential cross sections for the process $d(\gamma, K^-p)K^+n$ proceeding through the intermediate Θ^+ state at initial energy of 1.5 GeV with the proton–spectator emitted in the direction of an incident photon as functions of the K^- production angle in the nuclear lab frame. The notation of the curves is identical to that in fig. 4.

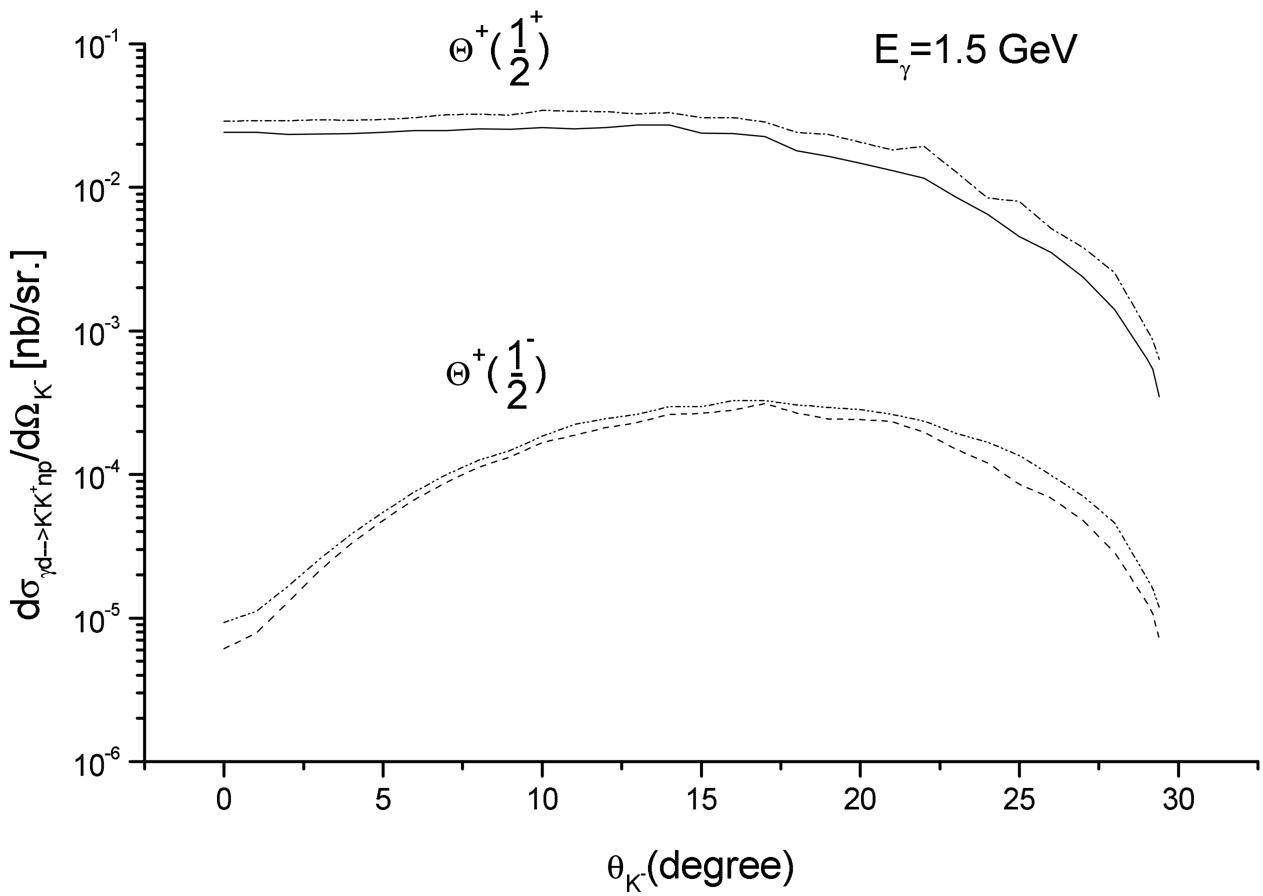

Figure 7: The inclusive K^--meson differential cross sections for the process $d(\gamma, K^-)K^+np$ proceeding through the intermediate Θ^+ state at initial energy of 1.5 GeV as functions of the K^- production angle in the nuclear lab frame. The notation of the curves is identical to that in fig. 4.

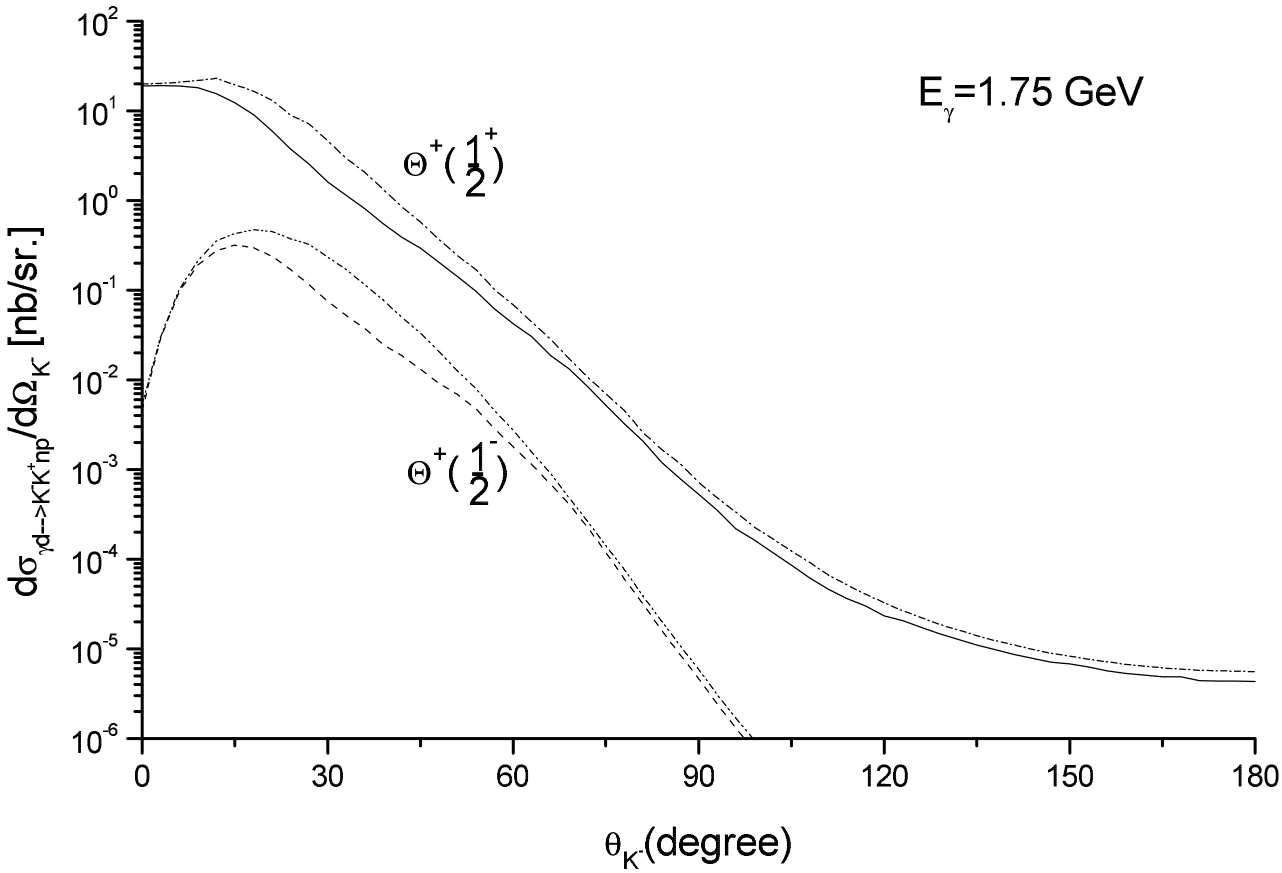

Figure 8: The same as in fig. 7 but for 1.75 GeV beam energy.